On Spectrophotometry in the Visible and Ultra-violet Spectrum.

By T. R. Merton, M.A., D.Sc., F.R.S., Professor of Spectroscopy in the University of Oxford.

(Received February 15, 1921.)

In a previous communication* the use of the neutral wedge for the determination both of the photographic and absolute intensities of spectrum lines has been discussed, and the results of its application to the study of certain phenomena relating to the spectra of hydrogen and helium have been given.† The method has been found to be simple and convenient for the study of the relative intensities and of the structure of broadened lines in the visible spectrum. There are, however, certain features of the method which under some circumstances limit its application; in particular the density of the "neutral" wedge increases with the wave-number, and for the investigation of the ultra-violet down to $\lambda = 2000$A, the method is at present inapplicable. Although it might be possible to construct wedges of crown glass with a very small angle for use in the ultra-violet, the fact that a number of such wedges would be required for different ranges would destroy the principal advantage of the method. Whilst no special precautions are required in the investigation of extended sources of light, it is evident that when small sources of light are used it is of the utmost importance to ensure that that portion of the slit which is behind the wedge is uniformly illuminated before the wedge is put into position, and in the case of selected regions of a source of light, *e.g.*, the spectrum from a particular point in the electric arc, it is only possible to obtain correct results by means of devices which entail a very considerable loss of light.

The present communication relates to a method which, whilst not superior to the wedge method in accuracy, has the advantage that it can be used in any part of the spectrum which can be photographed through quartz lenses and prisms, and its application to the extreme ultra-violet beyond $\lambda = 2000$A should present no serious difficulty. The method consists in crossing the dispersing system, *e.g.*, the prism of the spectrograph, with a very coarse grating, and reducing the length of the slit to a very small value. The grating is inserted between the prism and the camera lens of the spectrograph with the rulings perpendicular to the refracting edge of the prism, and a continuous

* Merton and Nicholson, 'Phil. Trans.,' A, vol. 217, p. 237 (1917).

† *Cf.* 'Phil. Trans.,' A, vol. 220, p. 137 (1919); 'Roy. Soc. Proc.,' A, vol. 98, p. 255 (1920).

spectrum thus appears on a plate as a dark central strip with a succession of other strips of different intensities on either side, the intensities of these orders being determined by the ruling of the grating and the width of the strips by the length of the slit. In the case of a discontinuous spectrum the "lines" are found to consist of dots of different intensities on either side of the central dot. It is evident that if the last dots which are just visible in the case of two lines are noted, a previous knowledge of the relative intensities of the different orders corresponding to these dots at once enables the relative intensities of the lines to be determined. It will be noted that the fact that the slit is reduced to a point not only enables different regions of a light source to be investigated without difficulty, but suggests a further application, which will be considered later, in the study of stellar spectra.

The experiments recorded in this communication have been made with a Hilger quartz spectrograph, with which the spectrum from the extreme red down to $\lambda = 2000$ A. is recorded on a plate 10 inches in length, and also with a constant deviation spectroscope with a camera attachment. Lord Rayleigh* has shown that in the case of a grating consisting of transparent bars of width, a, alternating with opaque bars of width b, the brightness of the mth order B_m is given by the expression

$$B_m : B = [1/m^2\pi^2] \sin^2 [am\pi/a+b],$$

where B would be the brightness of the central image if the whole of the grating were transparent; but it is probably impossible to produce gratings which conform absolutely to this ideal condition, and in my experiments all the gratings which were tried, whilst exhibiting qualitatively the distribution of intensity to be expected according to theory, showed anomalies of various kinds, which were due no doubt to irregularities in the ruling.

It is necessary, therefore, to calibrate the gratings, that is to say, to determine experimentally the distribution of intensity in the different orders. A number of gratings have been made and tested, and the most convenient ruling for use with the quartz spectrograph has been found to contain about twenty-five lines to the inch. Wire-wound gratings are useless for the present purpose, for a very small rotation of the grating about an axis parallel to the rulings completely alters the distribution of intensity in the different orders, by changing the ratio of the transparent to the opaque parts of the grating. It is also essential that the gratings should not be made by any method which would involve cutting a groove in a transparent surface, for in this case we should have, in addition to the

* 'Collected Papers,' vol. 1, p. 213.

above-mentioned anomalies, which are due to irregularities in the ruling, the still more disturbing effects, which are not independent of the wave-length, due to the form of the groove.

The method adopted* has been to coat a quartz plate with a very thin layer of lamp-black by holding it over a dish of burning toluene, and to flow over the surface when cold a small quantity of alcohol containing a very small trace of shellac, which seems to improve the sharpness of the edges when the grating is ruled. The ruling was performed with a bone tool on a shaping machine provided with an automatic feed, and the resulting grating was experimentally calibrated.

The calibration was carried out with the aid of a neutral wedge, for which the density step, as a function of the wave-length, had been determined according to the method described in the previous investigation;† an essentially similar method for determining the density of a medium in the form of a wedge has since been described by Slade and Toy.‡ For this purpose the constant deviation spectrograph was used, and the grating was set with the rulings parallel to the refracting edge of the prism, with the wedge set in the usual manner in front of the slit, which for this purpose was of such a length as to cover the whole length of the wedge. As a source of light, a mercury arc lamp was used, and individual radiations, *e.g.*, $\lambda = 4359$ A., were isolated by inserting absorbing screens in front of the lamp and by an appropriate choice of photographic plates.

The resulting pattern on the plate is shown in fig. 2*a*, in which the second groups of orders, beyond the points at which the values of $[am\pi/a+b]$, in the expression given above, become greater than π, are clearly visible. The relative intensities of the different orders were determined by measuring the heights of the orders on the plate, the relative intensities being proportional to $\log 10^{-1}[d_\lambda h_\lambda/m]$, where d_λ is the change of density per millimetre on the wedge, h_λ the height in millimetres of an order on the enlargement, and m the magnification of the slit on the enlargement. If the intensity of the central order be taken as unity, and if the intensity of the mth order be M, it is evident that, if a spectrum line, λ_1, gives an image on which the central order is just visible, and the image of another line, λ_2, is just visible in the mth order, the ratio of their intensities, I_{λ_2} and I_{λ_1}, will be given by $I_{\lambda_2}/I_{\lambda_1} = 1/M$. A calibration curve is given in fig. 1, in which values of $\log I$ are plotted against the corresponding orders. The arrow denotes the central image, the intensity of which has been made equal to unity, and the

* *Cf.* Wood, 'Physical Optics,' p. 211.

† *Loc. cit.*, p. 241.

‡ 'Roy. Soc. Proc.,' A, vol. 97, p. 191 (1920).

ordinates thus give the logarithms of the intensities of lines which are just visible in corresponding orders on the abscissa scale.

It is evident that the method is subject to the inconvenience that the scale of intensities is discontinuous, and in this respect it is inferior to the wedge method in its application to discontinuous spectra, though it is believed that estimates of the visibility of the last dot can attain a considerable degree of precision, since all such estimates are carried out over the same range of photographic density, and the asymmetry in the intensities of the orders on opposite sides of the central image, which was found on all the gratings, and which is clearly shown in fig. 1, is, in fact, an advantage, owing to the increase in the number of points available. It is also evident that, by a succession of exposures of different duration, the relative intensities of different lines can be linked up, in cases in which a single exposure fails to give sufficiently complete information. In its application to discontinuous spectra, the advantage of the method lies in the fact that it can be used in the ultra-violet, and photographs have been obtained over the whole range of wave-lengths, which could be photographed with the quartz spectrograph.

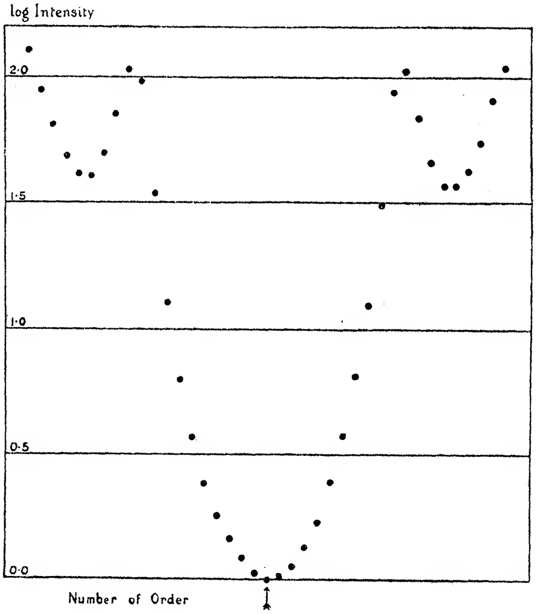

FIG. 1.

In the previous investigation* it has been shown that photographic intensities can be reduced to absolute values by adopting the positive crater of the carbon arc as a standard source of radiation, having a known distribution of

* *Loc. cit.*, p. 242.

intensity, the variation in the sensibility of the photographic plate for different wave-lengths and absorption of light by the spectrograph being thus eliminated. In fig. 2 is shown the pattern given by the positive crater of the carbon arc on a panchromatic plate, using the glass spectrograph with (B) the neutral wedge, and with (C) the grating, the helium lines being superposed as reference lines. In the visible portion of the spectrum the relation between the sensibility of panchromatic plates and the wave-length is of so complicated a character that a considerable number of exposures by the grating method might be required to elucidate it fully, and in this region it is more convenient to determine this relation (in which absorption by the spectrograph is included) by the use of the wedge; in the ultra-violet, where the relation of sensibility to wave-length is less complex, one or two exposures are sufficient to furnish all the information required. This relation must, of course, be determined for the particular plates which are used; with regard to the correction for dispersion when continuous and discontinuous spectra are compared, the reduction of photographic to absolute intensities, and other relevant considerations, reference may be made to the previous communication (*loc. cit.*).

The grating method appears to be more particularly applicable to the study of the distribution of intensity in continuous spectra, the structure of broadened lines, and the quantitative investigation of absorption spectra, for in these measurements the discontinuity of the calibrated intensities is of no consequence. The measurement here consists in observing at what wave-lengths the strip due to each order is just visible, and there are thus a considerable number of points each of a specified intensity which can be plotted against the wave-length. This is shown in fig. 2, C; the appearance of an absorption band (on one side of the minimum) is precisely similar to the pattern at either end of the spectrum in the figure, the violet end of the spectrum being in this particular case determined by the absorption of the glass prism, and the red end by the sensibility of the photographic plate. If a source of light of constant intensity, giving a continuous spectrum, is used, it is sufficient to take two exposures of the same length on adjacent portions of the same plate, interposing in the case of one of these exposures a layer of an absorbing substance under investigation in front of the slit; these two exposures yield the information required for determining the density of the medium as a function of the wave-length.

In a recent investigation, H. H. Plaskett* has applied the wedge method to the study of the continuous spectrum and of the bright hydrogen lines in the star γ Cassiopeiæ, using a single prism spectograph attached to the 72-inch

* 'Monthly Notices Roy. Astr. Soc.,' vol. 80, No. 9, p. 771 (1920).

reflector of the Dominion Observatory, and has obtained interesting results relating to the black body temperature of the star. The wedge was placed in front of the slit, as in laboratory experiments, and uniform illumination was secured by allowing the image of the star to trail forward and backward over the slit.

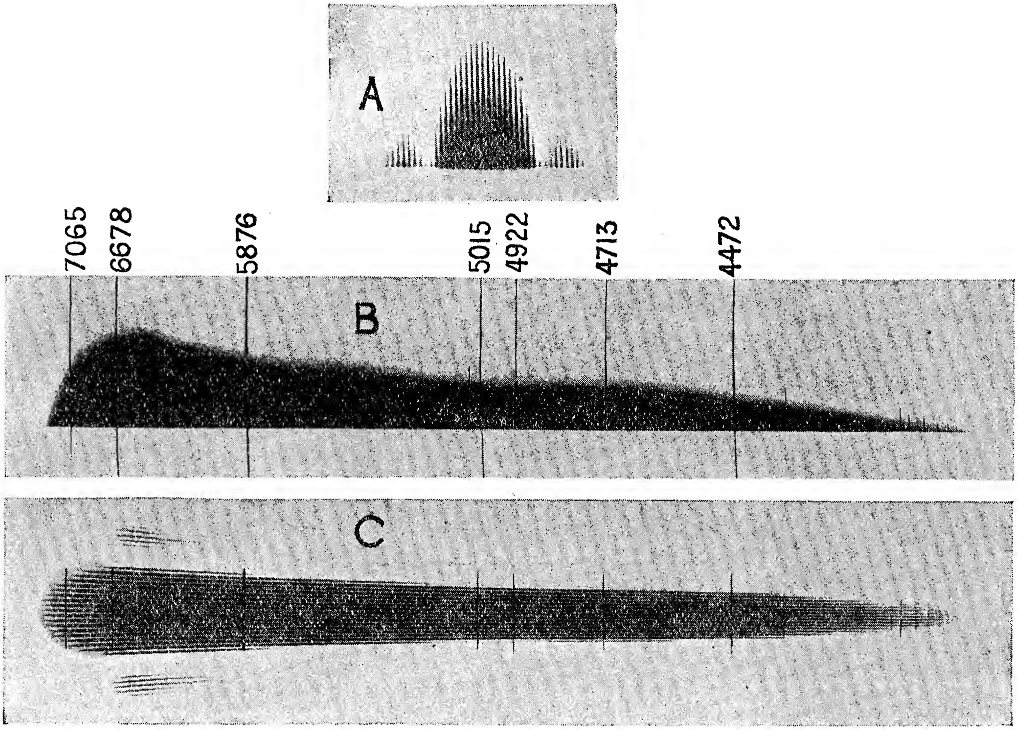

FIG. 2.

It would appear that the wedge method can only be applied to the study of stellar spectra by a procedure essentially similar to that adopted by Plaskett, and that instruments of very great light-gathering power are necessary; in Plaskett's experiments exposures up to two hours were given for γ Cassiopeiæ which is a star of photographic magnitude 2·01. I would suggest that the grating method is particularly applicable to the investigation of stellar spectra and that valuable results relating to the black body temperatures of stars might be obtained with telescopes of very moderate dimensions with the aid of an objective prism. In this case the star itself provides the beam of parallel rays which are produced in the laboratory by means of the collimator with the slit reduced to a pin-hole, and the objective prism is therefore directly applicable. It is only necessary to interpose a

grating of suitable ruling between the objective prism and the objective in order to obtain a spectrum photograph of a star essentially similar to that shown in fig. 2, C. It would appear that the exposures required for this purpose would not be unduly long.

The loss of light with an objective prism is very much less than when a slit spectroscope is used, and the common procedure of allowing the star to trail slowly in a direction perpendicular to the dispersion in order to widen the spectrum, is for the present purpose to be expressly avoided, with a consequent gain in brightness, the spectrum being in this case widened by the action of the grating. It is also clear that the exposure need only be of such a length as to register the faintest portions of the spectrum on the central image, the brighter portions being thus visible in the higher orders. From the expression $B_m : B = [1/m^2\pi^2] \sin^2 [am\pi/a+b]$ it follows that the brightness of the central order $B_0 : B$ will be equal to $[a/a+b]^2$, and in the case of a equal to b the exposure would only be four times as long as it would be without the grating and perhaps considerably shorter than it would be if the image of the star were allowed to trail to any considerable extent; but a smaller value of a/b would probably be necessary for the study of a number of phenomena such as the structure of the nova bands and the time of exposure would accordingly be greater.

A Superior Limit to the Age of the Earth's Crust.

By Henry Norris Russell, Professor of Astronomy in Princeton University.

(Communicated by Mr. J. H. Jeans, Sec. R.S. Received February 26, 1921.)

Considerations based upon radio-activity have often been employed to obtain estimates of the ages of minerals, and of the duration of geological time; but it does not appear to have been remarked that similar arguments can be used to assign a maximum age for the existing crust of the Earth.

Uranium is continually disintegrating with a "half period" of 5×10^9 years, and no process is known by which the supply can be renewed. It is probable that the proportion of this element in the Earth's crust was greater formerly than at present—the computed amount necessary to account for the survival of that which now exists increasing exponentially with the time interval, a thousand fold in ten half periods and a million fold in twenty.

The existing proportion of uranium may be derived from that of radium,

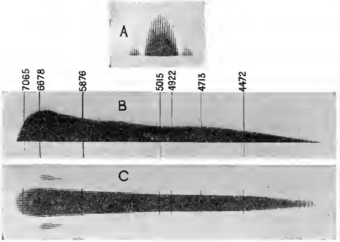

Fig. 2.